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A High-Efficiency Steam–Gas Plant for Combined Electrical Power and Heat Production

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Abstract—An original scheme of power plant for combined production of heat and electric power is considered in paper. A comparison is made of main thermodynamic and techno–economic characteristics of the setup proposed with the alternatives. A conclusion is made that the considered combined-cycle plant with high thermal efficiency, reduced weight-dimension characteristics and improved electrical–thermal production ratio can meet the requirements on energy-supply of mutual residential communities and industrial projects.

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INTRODUCTION

The critical situation in Russian energetics, caused by high wear of key assets, compels a search for new unconventional technological solutions, primarily in heat power engineering, which comprises about 67% of total power from power stations. Almost half of all operating fuel-burning power plants are working in the Heating Power Plant (HPP) regime.

The replacement of worn out steam-turbine power generating units with much more efficient combined-cycle units is offered in programs for the technical reequipment of heat power engineering. This is considered to be a general line of the development strategy of energetics in Russia.

However, when this idea is applied to power generating units of HPPs, the result can be antithetical. This is because heating units of CCGTs (Combined-Cycle Gas Turbines) with highly efficient electric power production in the condensation regime produce at maximum thermal load almost three times less heat than a steam-turbine power generating unit of the same power.Thus, the missing heat must be produced in boiler houses, reducing the overall efficiency of combined heat and power production.

For the correct analysis of different schemes for combined production of electric and heat power, an isolated district with complete satisfaction of its needs in electric power and heat should be considered.

In this case, the underproduction of heat energy is compensated by generation of additional heat in the local boiler house, while the underproduction of electric power is compensated by a condensation SDPP (State District Power Plant). For conditions of central Russia, the ratio of maxima of heat and electrical power loads should be assumed to be on the order of 2.5–3.0.

With such a correlation, the fuel heat utilization factor (FHUF) can be regarded as the main characteristic of thermal effectiveness:

$$\mathrm{FHUF} = \frac{N_e + Q_t}{H_t}$$

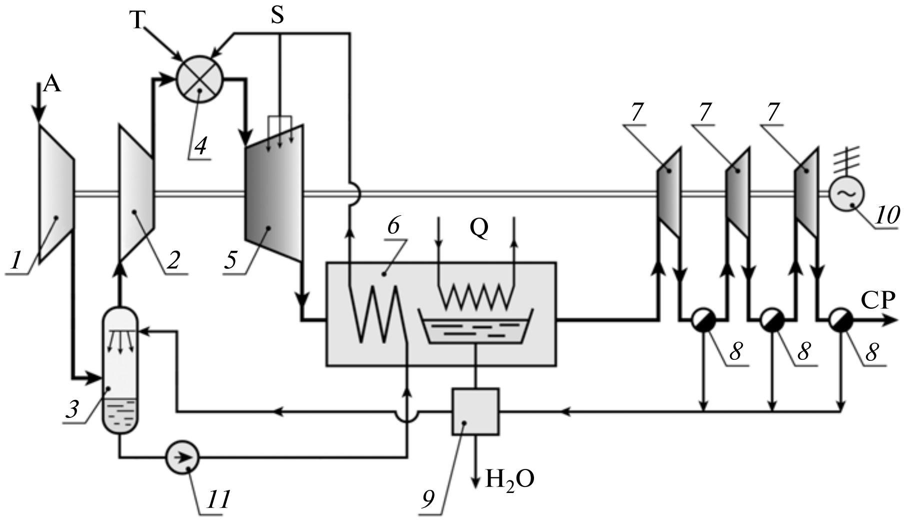
(where N_e is the useful electric power, MW; Q_t is the output heat power, MW; and H_t is the overall energy of fuel consumed), and the following coefficient of efficiency is a criterion of electric power production efficiency on heat consumption:

$$\eta_e = \frac{N_e}{Ht - \dfrac{Q_t}{\eta_\kappa}},$$

where η_e is the electric power production efficiency on heat consumption; η_κ is the kettle efficiency of the heat boiler house.

If binary combined-cycle power plants with steam take-off for heating purposes from tail sections of a steam turbine are considered the main alternative to modern steam-turbine power plants, then it should be noted that, along with the obvious advantages of the former, there is a significant intrinsic drawback: the FHUF of CCGTs is always lower than that of STPs (steam power plants). The reason is that the main type of losses of heating units are those with output gases; those of CCGTs are several times higher than those of STPs due to the former's much higher excess air coefficient.

For one of the top and most widespread thermal-clamping steam turbines, T–250/300–240, the FHUF is 84.7%, which is close to the limit value for real characteristics of the steam-turbine cycle. At the same time, for one of the largest CCGT TPPs in Russia (Northwest TPP JSC Lenenergo), the FHUF = 81.7% for CCGT 450T; according to the design index of the thermal-



Scheme of the CCGT plant for combined production of electric power and heat: *1* is the low-pressure compressor; *2* is the high-pressure compressor; *3* is the air cooler; *4* is the combustion chamber; *5* is the gas turbine; *6* is the heat exchanger; *7* is the expansion machine unit; *8* is the separator; *9* is the condensate refinement unit; *10* is the electric generator; *11* is the feed pump; A is the air; T is the natural gas; S is the steam; CP are the combustion products; Q is the water of the heating-system.

clamping CCGT 230, created completely on the basis of domestic equipment [1] according to the project design of the Dzerzhinsky Institute of Heat engineering (VTI) (Moscow), the FHUF is 81.3%.

From this point of view, the scheme of a CCGT TPP presented below is of great interest; it makes it possible to obtain a FHUF of more than 100% in a combined cycle not only theoretically, but for a real operating plant at the achieved level of parameters and sophistication of separate units of the technological scheme.

SCHEME OF THE PLANT, FEATURES, AND PRINCIPLE OF OPERATION

A schematic diagram of the setup, as well as a comprehensive design study of the basic units, was performed by a group of specialists of the JIHT RAS (Moscow) and the conversion enterprise GosMKB Rainbow (Dubna) in the framework of project no. 1587 of the International Science and Technology Center. A scheme of the plant patented in the RF [2, 3] is presented in Fig.1 in simplified form.

Free air is compressed by the low-pressure compressor (*1*) to the pressure of 6.3 at and supplied to a mixing-type air cooler (*3*), where it is saturated by water vapors and cooled through water evaporation. Utilization of the air cooler makes it possible to keep the air temperature at the output of the high-pressure compressor (*2*) at the designed level of the initial (basic) gas-turbine engine (446°C) and to maintain the safe operation mode of the blade row.

Compressed air, natural gas, and water vapor at a temperature of 285°C, ensuring the parameters of the working medium before the turbine group of the compressor actuator of 64 at/1310°C at the excess air coefficient of $\alpha = 1.12$, are supplied to the combustion camera of the CCGT.

Water vapor is used to cool down elements of the turbine group, which makes it possible to increase the working medium temperature over the calculated one for the initial GTP (gas-turbine plant), while keeping the metal temperature of the blade row below the designed level.

The vapor–gas mixture at the output of the group of driving turbines comes to the regenerative heat exchanger (*6*), where generation and overheating of the injected vapor occurs, along with warming of the heating-system water (Q) .

The main operation feature of the proposed scheme is that high pressure (3.05 at) is kept in this heat exchanger; this naturally increases the partial pressure of water vapors and makes it possible to condense them at a temperature high enough to heat the heating-system water up to the standard parameters of the cogeneration system.

After the heat exchanger (*6*), the vapor–gas mixture is expanded to atmospheric pressure in the expander (*7*); as this takes place, the effective work is performed and some additional amount of water is condensed, which is captured by the separator of condensed moisture (*8*).

This water, along with the main condensate flow from the heat exchanger (*6*), comes to the system of condensate collection and refinement (*9*) and is then directed to the air cooler (*3*) and heat exchanger (*6*) for vapor generation and overheating. The excess of

Comparison of energy production and fuel consumption

Attribute	Heating unit type			
	STP	CCGT		
	T-250/300-240	STP 450T	STP 230	Proposed plant
Useful electric power, MW	231.9	433.8	213.6	62.4
Useful heat power, MW	384.0	410.5	160.5	77.8
Fuel consumprion, MJ/s	726.8	1033.1	460.2	135.7
FHUF, %	84.7	81.7	81.3	103.3
Efficiency of electric power production on heat consumption, %	71.9	72.2	73.3	115.9
Relative heat generation, KJ/s per KW of useful power	1.656	0.946	0.751	1.247
Peak power of enclosing boiler house, kJ/s	–	0.710	0.905	0.409
Total fuel consumption, kJ/s	3.134	3.128	3.107	2.606
including:				
of the plant	3.134	2.381	2.154	2.175
of the enclosing boiler house	–	0.747	0.953	0.431
Fuel consumption, %	100.0	99.8	99.1	83.2

water condensed from the combustion products can be used for any purpose.

A steam–gas plant created by this scheme on the basis of GTP AL-31 equipment would have the following main characteristics:

(1) useful electric power of 62.4 MW;

(2) useful heat power of 77.8 MW;

(3) efficiency of electric power production of 115.9% on heat consumption in the nominal regime and 50.7% in the condensation regime (at heat-consumer disconnection);

(4) air consumption of 52.4 kg/s;

(5) excess of condensate of 8.6 ton/h.

HEAT EFFICIENCY OF THE SCHEME

Direct comparison of the heat efficiency of heating units of different types is difficult because of disproportionate heat distribution to the consumer. Comparison of specific fuel consumption in the nominal regime of electrical energy and heat distribution with equalization of useful heat production is one possible technique. This equalization is carried out by introducing the enclosing boiler house into calculation. A comparison of four different ways of combined production of electric power and heat is presented in the table.

FHUF AND ELECTRIC POWER PRODUCTION EFFICIENCY ON HEAT CONSUMPTION

The main advantage of the scheme proposed is in the possibility to obtain the maximum heat efficiency up to FHUF > 100% not only theoretically but at a real plant. It only appears to violate the law of conservation of energy in this case. The fact is that calculation of all characteristics of the plant, according to conventional calculation techniques including the efficiency and FHUF, is made on the lowest fuel calorific value. Thus, water vapor formed during the combustion of hydrogen of the fuel is understood to leave the plant in gaseous form. This happens in most power plants; if condensation of vapor from combustion products is provided, then it is a vapor that has been injected earlier, and the heat of its condensation cannot be used usefully owing to the low temperature level of the condensation process.

Condensation in this scheme is performed at a pressure considerably higher than atmospheric pressure, which accordingly raises the temperature of the process and makes it possible to use the released heat for heating purposes. As this takes place, the vapor injected earlier in the combustion chamber is condensed, as well as the vapor generated from the hydrogen of the fuel. So, the quantity of heat that is usefully used is larger than that of the fuel determined on the lowest calorific value. It is obvious that, if the plant characteristics are calculated

on the basis of the highest fuel calorific value, then there would be no paradox like this.

The second reason for such a high value of the FHUF is related to the abnormally low heat waste with exhausted gases. Several stages of working medium expansion after vapor cooling and condensation further reduce the temperature of exhausted gases. Design temperature at the output of the plant is 49°C; the specific weight of the combustion products (kg/kW of useful power) is several times lower than for conventional GTPs because of a small excess oxidant ratio ($\alpha = 1.12$ instead of 2–3).

Useful utilization of the heat quantity exceeding that determined by the lowest fuel calorific value also makes it possible to obtain an efficiency of electric power production on heat consumption of more than 100%; this gain in the relative form is more considerable than for the FHUF, because its quantity is related to a smaller quantity of heat.

THE MAIN PREMISES FOR EQUIPMENT CHOICE AND CALCULATION OF THERMAL SCHEME OF THE PLANT

The basic principle for choosing the prototypes for different nodes of CCGTs and for calculation of the thermal scheme is the utilization of units and assemblies that are either produced by local power plant engineering or prepared for adaptation, i.e., equipment whose design and manufacture present no serious difficulties. The gas generator of the typical GTP AL-31 power plant, manufactured by the scientific-production association Saturn, is proposed as the turbo-compressor group, the main element of a CCGT.

Preliminary analysis has shown that the following changes have to be introduced to the construction of a GTP in the proposed scheme:

1) in order to keep the maximum value of mechanical stress of the compressor blade row at the designed level, the rate of air consumption is reduced from 63.5 to 52.4 kg/s;

2) in order to increase the total compression ratio, a compressor ND is upgraded by a group of stages;

3) the cooling agent in the cooling system of the air–gas channel of the GTP is changed from air to steam; the construction of the cooling system is maintained completely. Steam consumption in the cooling system is defined by the initial steam pressure and the hydraulic resistance of the cooling system in this case. Abundant scientific evidence shows that, for steam cooling, the temperature of the working medium can be raised by 90–110°C; the temperature of the metal of the blade row is kept at the same value. The initial temperature of the working medium of 1310°C in this scheme is taken with a considerable reserve; it is 53°C higher than the designed value for GTP AL-31. The metal temperature of the most stressed nodes of the CCGT is below the designed value, which has a beneficial effect on reliable performance of the plant.

Preplanning performed in conjunction with the project design team of the Saturn scientific-production association showed that the air–gas channel of the gas generator is in a position to pass through the designed flow of the working medium; the work turbine of the GTP should be redesigned owing to the increase of the rotor blade length of the last stages. Utilization of a work turbine from another device manufactured by Saturn is a possible alternative solution.

The construction of the mixing air-cooler and heat-exchange equipment is based on standard elements and thoroughly designed by the specialists of the scientific-production association Raduga.

The averaged aerodynamic characteristics of the cylinder ND stages of the condensing steam turbine with regard to the efficiency reduction of the air–gas channel, caused by condensed moisture drop-out, were used for expander calculation.

The main principle applied at the calculation and design stages is the creation of a plant consisting of a finite number of factory-assembled units, which makes transportation by standard flatcar possible. This required utilization of intensified heat-exchange processes, which resulted in favorable weight-cost characteristic reduction of the equipment, but it also led to some reduction of heat efficiency.

POWER–HEAT PRODUCTION RATIO

Another aspect of various CCGT schemes for combined production of power and heat that should be touched on briefly is the ratio between electric and thermal load. For the climate zone of the main part of Russia, the ratio between the maximum consumption of heat and electric power in a cogeneration system is at the level of 3–3.5. From this point of view, a ratio of N_{heat}/N_{el} for steam-turbine plants is close to optimal, because the basic portion of heat consumption can by satisfied by a TPP, while the variable component of thermal load can be provided by district boiler houses[1].

The ratio mentioned above is much worse for steam–gas plants: 0.946 for CCGT 450T and 0.751 for CCGT 230, which requires the construction of district boiler houses of higher power and forces them to supply the main portion of the heat for consumers.

The proposed scheme has a N_{heat}/N_{el} ratio equal to 1.247 and occupies an intermediate position between steam-turbine and binary combined-cycle heating units and makes it possible to reduce significantly the required power for district boiler houses, as compared with the alternative of CCGT TPP construction of the binary type.

[1] For T-250/300-240, this ratio is 1.656, i.e., about half of the required value.

Several advantages of the proposed scheme should also be pointed out. Utilization of more lightweight and cheaper gas-turbine equipment as the main source of energy production, with moderate parameters of steam and heat exchangers of high temperature pressure, made it possible to design a plant of low specific capital expenditure (SCE). According to preliminary estimates, SCE for the proposed scheme for the same electric power will be 15–20% lower than for heating CCGT, while heat output of the former is considerably higher.

CONCLUSIONS

The question of the necessity to create decentralized energy sources is considered during the concept design for Russia's energy strategy. This is owing to the disastrous condition of heating mains from large TPPs and high heat waste during heat transfer over considerable distances.

The proposed CCGT plant with a lower weight-size characteristic and moderate production of electric and heat power will perfectly fulfill the energy supply requirements of many residential communities and industrial objects.

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